THE EFFECT OF CONICAL AND SPHERICAL SHAPE OF DIMPLE'S BOTTOM PROFILE FABRICATED ON THE SHAFT SURFACE IN JOURNAL BEARING

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ABSTRACT

Growing concerns over engine emissions have accelerated the search for alternative energy sources, with hydrogen emerging as a promising solution to reduce dependence on non-renewable fuels. In modern automotive systems, bearings are essential for achieving performance targets by supporting rotating components, carrying loads, and facilitating torque transfer. The effectiveness of introducing dimples on the contact surfaces of journal bearing depends on various factors. Careful consideration needs to be clarified as the wrong selection would have a detrimental effect on the surface. In this study, the conical and spherical shapes of the dimple's bottom profile were fabricated on the shaft surface. The experiment was conducted by using a journal-bearing test rig with a 0.5 length-to-diameter ratio, made of Stainless steel SS304, and lubricated by mineral-based oil VG68. The experiment was conducted under various operating conditions. It was observed that the spherical shape demonstrated significant improvement in terms of friction coefficient, load-carrying capacity, and minimum oil film thickness compared to that of the conical shape and smooth surface respectively.

Keywords: *Journal bearing, Surface texture, Tribology, Lubrication, Hydrogen engine*

1.0 INTRODUCTION

The growing demand for sustainable transportation has catalyzed significant advancements in alternative propulsion technologies. Among these, hydrogen-fuelled internal combustion engines (H_2ICE) have garnered increasing interest as a viable near-term solution due to their clean combustion characteristics and compatibility with existing engine architectures [1]. Unlike conventional fossil fuels, hydrogen combustion generates no carbon-based emissions, effectively mitigating pollutants such as unburned hydrocarbons (HC) and carbon oxides [2]. This renders H_2ICE a promising candidate for achieving cleaner mobility while leveraging established manufacturing, supply chain, and recycling infrastructures.

As the automotive industry transitions toward sustainable propulsion technologies, including hybrid, battery-electric, and hydrogen-powered engines, optimizing key engine components remains imperative. Among these, journal bearings play a crucial role in ensuring efficiency, durability, and overall powertrain performance [3]. Bearings within H_2ICE systems are subjected to distinct operational challenges, including altered combustion characteristics, lubrication constraints, and thermal variations. These factors directly influence material selection, design optimization, and maintenance strategies. A comprehensive understanding of these challenges is essential for developing high-performance bearing solutions that enhance the reliability and longevity of hydrogen-powered engines.

The enhancement of tribological characteristics is critical in minimizing energy losses and optimizing mechanical efficiency. Various strategies have been explored to achieve this objective, including optimization of operating conditions, enhancement of lubrication properties [4], diversification of lubricant sources [5-12], and refinement of geometric design parameters [13]. Among these approaches, surface texturing has emerged as a promising technique, wherein contact surfaces are modified to improve frictional performance and wear resistance. This concept, inspired by natural surface formations, introduces engineered microstructures such as dimples that influence lubricant distribution and third-body debris entrapment, thereby mitigating abrasive wear [14]. The presence of these microstructures facilitates lubricant retention, particularly under starved lubrication conditions, by enabling the redistribution of entrapped lubricant through pressure-induced squeeze-out mechanisms. This, in turn, minimizes friction and wear on interacting surfaces.

Lubricants serve as a critical medium for facilitating relative motion between contacting surfaces, functioning through mechanisms such as rolling, sliding, or shearing [5]. The selection of an appropriate lubricant is contingent upon key properties, including viscosity, thermal resistance, and cold-flow characteristics [6]. The viscosity index is a fundamental parameter in lubricant evaluation, with higher values indicative of superior stability across varying temperatures [15]. Low-viscosity lubricants are generally discouraged due to their propensity for displacement under minimal loading, thereby compromising surface protection [7]. Owing to its exceptional performance, mineral-based lubricants constitute over 70% of the global lubricant supply [4], with VG 68 selected as the reference lubricant for the present study.

The efficacy of surface texturing is highly dependent on multiple factors, including dimple geometry, spatial distribution, location, concentration, motion type, operating conditions, and bottom profile characteristics. Careful parameter selection is imperative, as improper dimple configurations have been reported to induce adverse effects on contact surfaces [16-18]. Since the initial findings on surface texturing in 1996, extensive research efforts consist of both experimental and numerical have been undertaken worldwide to elucidate its tribological benefits [19]. These investigations encompass diverse applications such as thrust bearings, mechanical seals, and piston rings. While most studies have been conducted theoretically, advancements in simulation technology have enabled the numerical resolution of increasingly complex governing equations. Furthermore, modern simulations now incorporate critical operating conditions, including mass conservation principles, inter-asperity interactions, thermal deformations, magneto-hydrodynamic effects, and transient phenomena. Nevertheless, the experimental validation of surface texturing remains limited, primarily due to constraints in machining capabilities required for fabricating intricate dimple structures on contact surfaces.

1.1 The Tribological Performance of Journal Bearing with Textured Surfaces.

One of the key geometrical factors extensively studied in surface texturing is the shape of the dimples fabricated on contact surfaces. The geometric parameters of dimples, including diameter, length, and depth, are crucial in determining their effectiveness in enhancing performance. Commonly investigated dimple shapes include circular, cylindrical, rectangular, and elliptical profiles, among others. Certain shapes may contribute to additional hydrodynamic pressure generation, while others may exhibit negligible improvements. Furthermore, the efficacy of a specific dimple shape is highly dependent on the operational conditions, as some configurations may perform optimally in one scenario but yield suboptimal results in another. Consequently, there is no universally optimal dimple design applicable across all operating conditions, and the search for an optimized combination becomes increasingly complex when considering the multitude of factors influencing operational performance.

Numerous studies have been conducted to evaluate the effects of surface texturing on journal bearings. Research on transient behaviors of journal bearings with surface texturing has demonstrated that the effectiveness of texturing in enhancing load-carrying capacity is highly dependent on its circumferential positioning [20-22]. Additionally, the incorporation of textured conical hybrid journal bearings with electrorheological (ER) lubricants has been found to significantly improve minimum oil film thickness, thereby reducing metal-to-metal contact [23]. Investigations into internal combustion engine bearing shells with surface texturing have reported friction reductions of 13% to 18% in comparison to non-textured counterparts [17]. Furthermore, the application of spherical micro-dimples on bearing surfaces has been observed to enhance bearing stability and reduce frictional losses [24]. Recent studies have also explored the impact of textured surfaces in starved hydrodynamic lubrication regimes, revealing that textured surfaces effectively facilitate lubricant replenishment within the contact zone under starved conditions [25].

In the context of static behavior analysis, researchers have evaluated journal bearings with four distinct dimple patterns—chevron, sawtooth, oblong, and aligned dimples. It was observed that the chevron and oblong dimple patterns contributed significantly to improved journal bearing performance [16]. Additionally, investigations into continuous-grooved textures in hydrodynamic lubrication regimes have demonstrated that circular textures yield superior lubrication performance at lower area densities, whereas square textures provide enhanced tribological performance when area density exceeds 25% [26]. Another study examined the performance of textured journal bearings under slip boundary conditions and pseudoplastic lubrication, revealing that the combination of slip-texturing and rheological transitions from Newtonian to pseudoplastic lubricants resulted in increased maximum pressure, reduced temperature rise, and lower friction force [27]. Furthermore, numerical analyses of hydrodynamic journal bearings incorporating partial texturing and journal misalignment have shown that partial texturing significantly enhances bearing performance, primarily due to the micro-pressure recovery mechanism. These improvements are particularly pronounced at high eccentricity ratios, greater misalignment angles, and when the alignment angle approaches 0° or 180° [18].

Another critical parameter in determining the influence of dimples is their placement on either the stationary or moving surface, or both. A study investigating various bottom dimple profile shapes found that applying dimples to the moving surface (journal) enhances lubricant flow into the contact region, thereby improving minimum oil film thickness [28]. Experimental studies assessing the effects of dimple placement on the journal, bearing, or both surfaces have revealed that dimpling the moving surface can yield either performance improvements or degradations, depending on specific operating conditions [29].

In this study, conical and spherical dimple bottom profiles were fabricated on the moving (journal) surface rather than the stationary (bearing) surface. The performance of these dimples will be evaluated using a journal-bearing test rig, with results compared against those obtained from smooth surfaces.

2.0 EXPERIMENTAL PROCEDURE

The journal-bearing test rig used in this study is shown in Figure 1. It was specifically designed to measure and determine key parameters in journal-bearing operation. The machine operates within a rotational speed range of 1800 rpm and supports a radial load of up to 120 N. While higher radial loads could be accommodated, additional modifications to the setup may be required.

This journal-bearing test rig comprises several essential components, including a journal driven by an electric motor, a bearing, a lubricant oil supply tank, a lubricant oil collector, and a sturdy steel frame. The rig is also equipped with six high-accuracy pressure sensors that monitor hydrodynamic pressure along the bearing circumference. Additionally, a load cell is integrated into the system to measure friction torque. All sensor outputs are connected to a data acquisition system, enabling real-time data collection and monitoring.

The journal and bearing components are manufactured from Stainless Steel 304, as illustrated in Figure 2, with their respective material properties listed in Table 1. Furthermore, the test rig features a lubricating circulation system, ensuring that lubricant oil collected from side leakages is pumped back into the supply tank for continuous operation.

2.1 Methodology

To conduct the test, approximately five liters of lubricant oil were first added to the oil supply tank. This volume was sufficient for the journal bearing to operate within the oil circulation system. The rotational speed was then set using the speed controller, and the dead weight was placed on the load holder.

Before initiating the test, it was essential to tighten the nuts securing the load cell to the lever arm. This step was necessary to prevent excessive vibrations during startup. Once the machine was running and had reached a stable condition, the nut was loosened to ensure that the bearing and load cell were not rigidly attached to the body frame.

When the oil level in the collection tank reached a sufficient level, the oil circulation pump was activated. Two critical control measures required careful monitoring during the test: the oil level in the supply tank and the oil supply temperature. Maintaining consistent inlet oil pressure and temperature across all test runs was crucial for ensuring accurate, reliable, and comparable data collection.

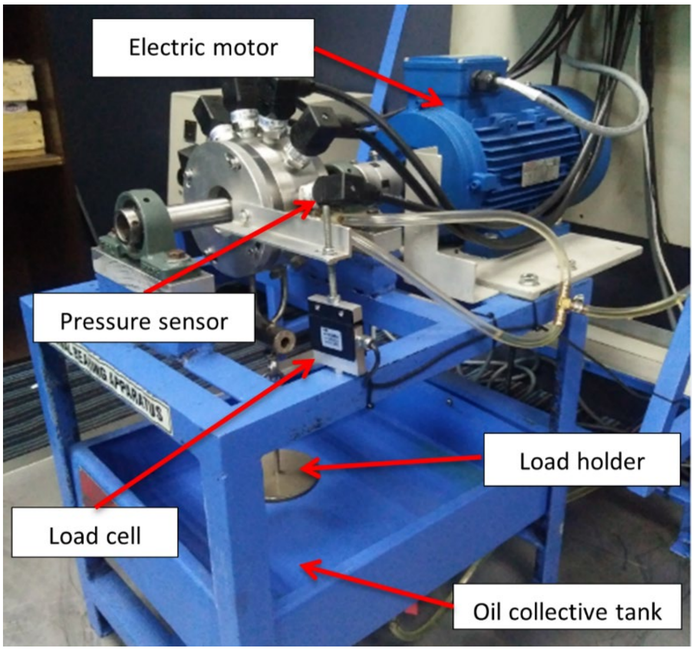

Figure 1: Journal bearing test rig

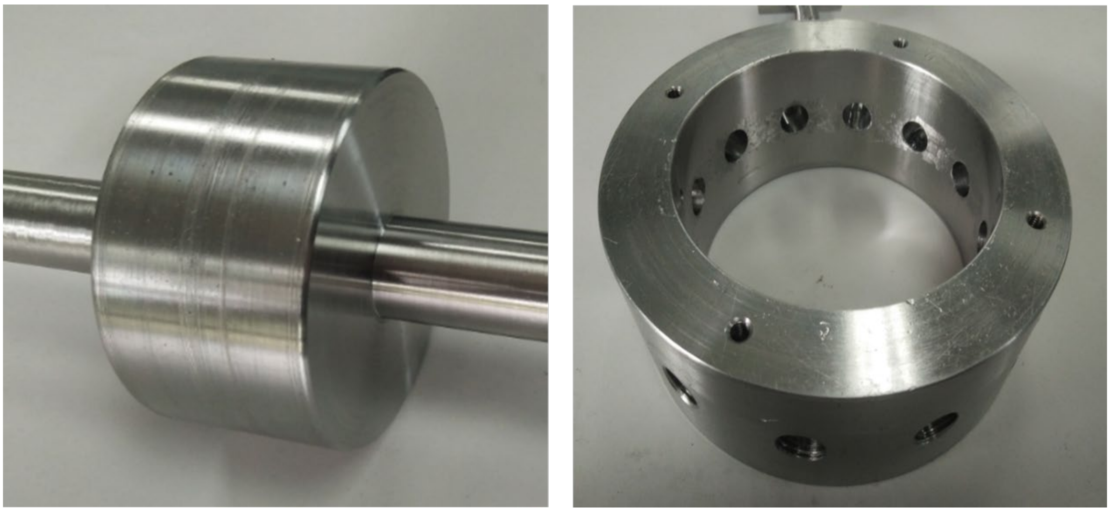

Figure 2: Journal (left) and bearing (right) made of Stainless steel 304

Table 1: General specification of the journal and bearing

Parameter	Value
Journal Material	Stainless steel 304
Bearing Material	Stainless steel 304
Journal diameter	99 mm
Bearing diameter	100 mm
Bearing length	50 mm
Radial clearance	0.5 mm
Length to diameter ratio	0.5

2.2 Surface Texturing on The Journal Surface

Two types of dimples were introduced in this study: spherical and conical. Figure 3 illustrates the dimple shapes and their geometric configurations on the shaft. The fabrication process required specialized drill kits, and the dimples were precisely machined using a CNC machine to ensure high accuracy. The dimples were arranged in an equilateral triangular matrix, as depicted in Figure 4.

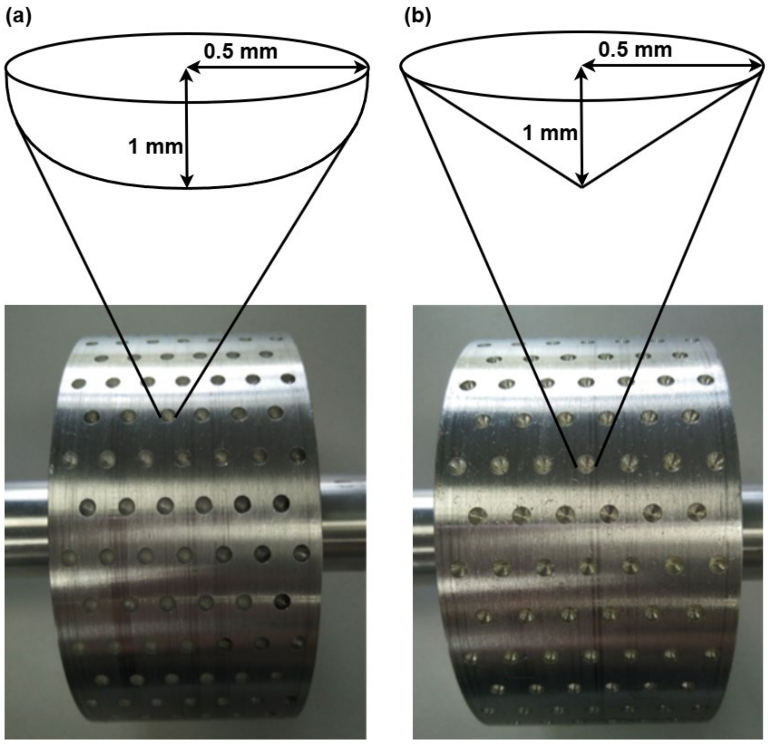

Figure 3: The dimple's bottom profile and its geometry of spherical (a) and conical (b)

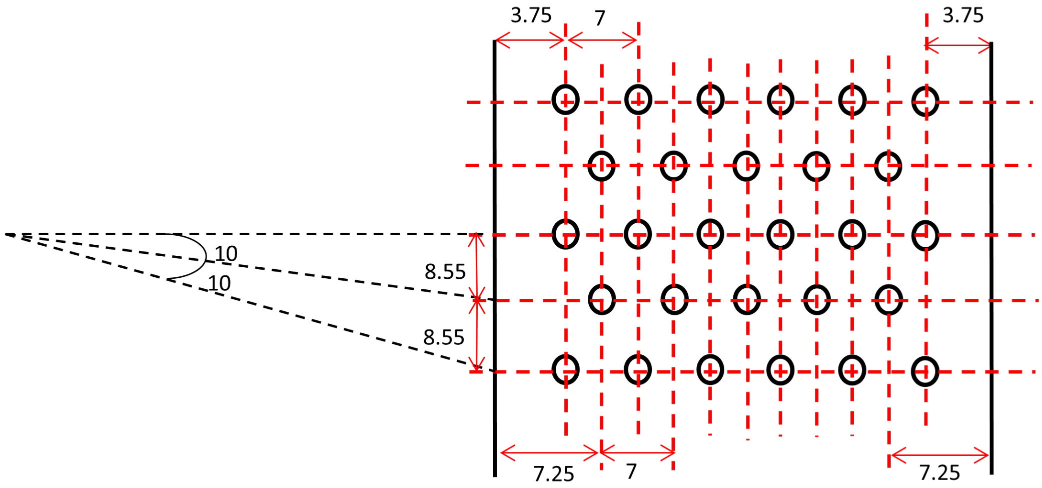

Figure 4: The dimple arrangement on the journal surface. All dimensions are in millimeters (mm)

2.3 Experiment Conditions

The experimental conditions for the journal-bearing experiment are summarized in Table 2. The selected speed range of 200 to 1000 rpm was chosen to analyze the tribological behavior of hydrodynamic journal bearings under low-to-moderate rotational speeds, which are crucial in hydrogen engine operations. This range includes idling conditions and low-speed transient phases, such as startup and shutdown, where lubrication performance and frictional characteristics play a key role in bearing wear and efficiency.

A duration of 20 minutes was sufficient for the bearing system to reach a stable hydrodynamic lubrication regime. Measurements were consistently conducted under steady-state conditions. To ensure this, startup times were allocated for thermal stabilization. Between tests, key parameters such as temperature and flow rate were carefully monitored until stabilization was achieved.

Table 2: Experimental condition for journal-bearing test

Parameter	Description
Radial load	10N / 20N / 40N / 60N / 80N / 100N
Shaft speed	200rpm / 400rpm / 600 rpm / 800 rpm / 1000 rpm
Duration	20 minutes / cycle
Oil tank level control	80 %
Oil inlet temperature	35 ºC
Lubricant	Shell Omala VG68

The lubricant oil VG68 has a kinematic viscosity of 65.3 cSt at 40°C and 11.9 cSt at 100°C. The oil temperature and viscosity along the bearing circumference were assumed to remain constant. Each test was conducted in triplicate to ensure the reliability of the obtained data.

2.4 Data Collection and Analysis

In the journal-bearing test rig, pressure readings from the top half circumference were recorded using pressure sensors to determine the eccentricity ratio. Simultaneously, load cell readings were used to calculate the friction torque and friction coefficient. Other journal-bearing parameters, including load-carrying capacity and minimum film thickness, were determined analytically.

3.0 RESULTS AND DISCUSSION

The analysis focused on the effects of surface texturing on the moving surface (shaft or journal) rather than the bearing surface. Key journal-bearing parameters, including the friction coefficient, load-carrying capacity, and minimum oil film thickness, were evaluated. Two types of dimples with different bottom profiles which are conical and spherical were investigated, and their performance was compared to that of a smooth surface.

3.1 The Effects of Different Dimple's Bottom Profiles on The Friction Coefficient.

In Figure 5(a), at a fixed shaft speed of 200 rpm, the friction coefficient was observed to decrease with increasing load. A similar trend was found at a higher speed of 1000 rpm, as shown in Figure 5(b). Conversely, at a fixed radial load, an increase in shaft speed resulted in a higher friction coefficient, as illustrated in Figures 6(a) and 6(b).

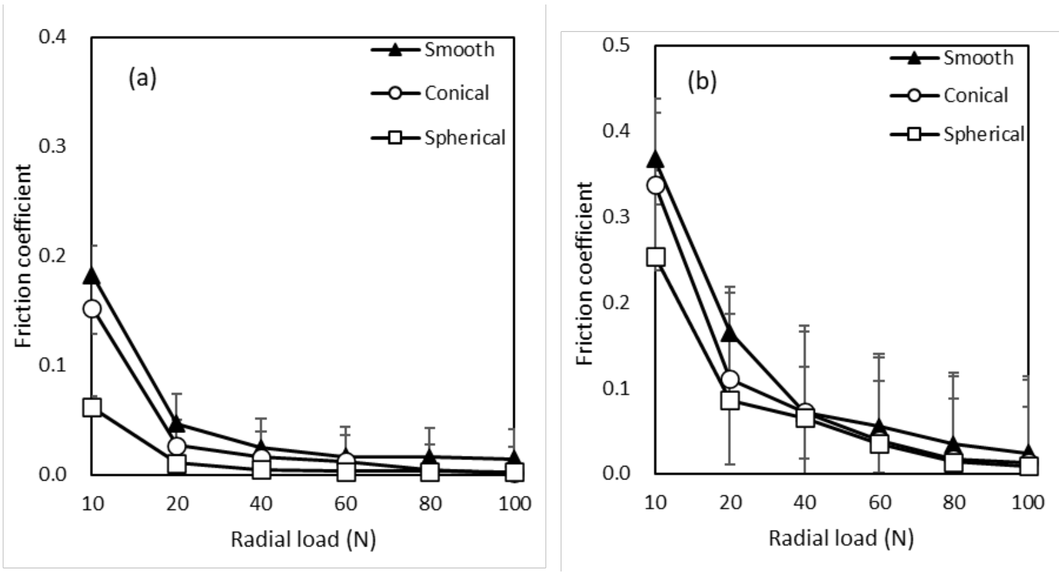

Figure 5: Friction coefficient at a shaft speed of 200rpm (a) and 1000rpm (b)

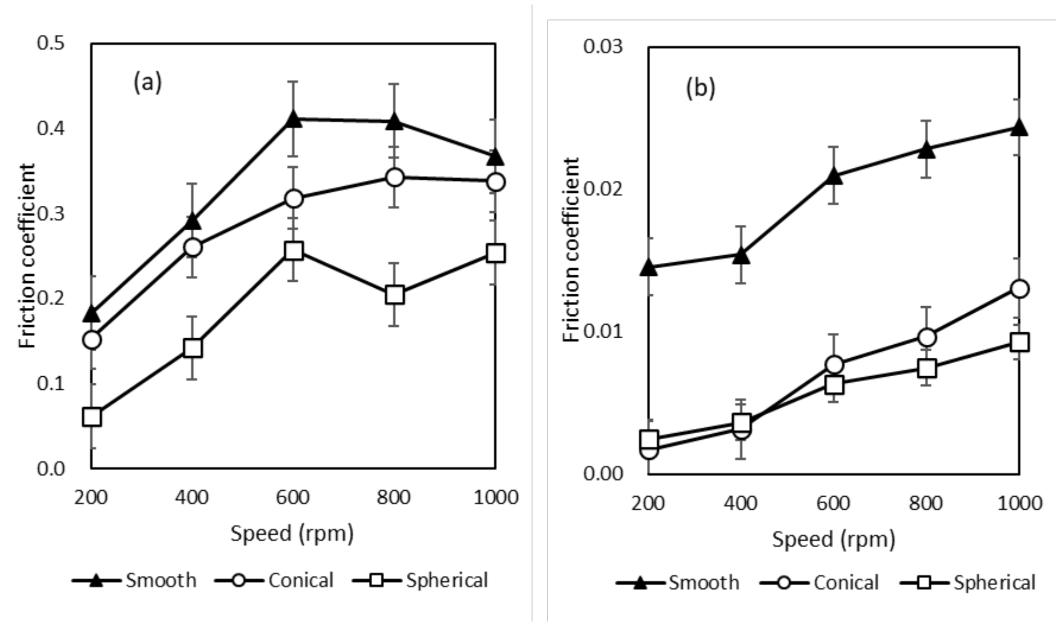

Figure 6: Friction coefficient at a radial load of 10N (left) and 100N (right)

The experimental results in this study align with those of Galda et al. [29], who reported a friction reduction of over 57% when texturing the journal surface with spherical dimples compared to a smooth surface. Similarly, in this study, the presence of surface textures—both spherical and conical—on the shaft reduced the friction coefficient relative to a smooth surface. Among the tested profiles, the spherical bottom shape consistently exhibited a lower friction coefficient than the conical shape under all operating conditions. At fixed loads of 10N and 100N, the spherical shape demonstrated 34.8% and 17.7% lower friction coefficients, respectively, compared to the conical shape.

Both dimple profiles shared common geometric parameters, including depth, aspect ratio, density, and arrangement. However, the spherical shape had a 138% larger volume than the conical shape, which likely contributed to its superior friction reduction performance. The percentage difference in friction reduction between this study and that of Galda et al. [29] can be attributed to variations in experimental setups, such as differences in applied load, dimple depth, lubricant properties, and operating conditions, as summarized in Table 3.

During journal bearing operation, dimples on the shaft surface caused a pressure drop in the dimple area. According to Nanbu et al. [28], the higher pressure outside the dimple region led to greater elastic deformation at the dimple edges. As the pressure decreased, the volume of the deformed dimple shrank, squeezing lubricant out of the dimple and providing additional lubrication. This phenomenon, commonly referred to as the squeeze effect, was also observed by Gropper et al. [30], who identified the buildup of pressure at the dimple inlet as a key factor in this process. The larger volume of the spherical dimples facilitated a higher micro-lubricant flow, supplying excess lubricant to the journal bearing and ultimately reducing friction more effectively than the conical shape.

Table 3: Experimental setup comparison

Parameter	Galda et al (2019)	Experimental data
Journal material	Hardened 42CrMo4 steel	Stainless steel 304
Bearing material	CuSn10P bronze	Stainless steel 304
Journal diameter (mm)	80	99
Bearing diameter (mm)	80.1	100
Bearing length (mm)	45	50
Radial clearance (mm)	0.05	0.5
Dimple depth (µm)	53	1000
Dimple diameter (mm)	0.75	0.5
Load (N)	6000	10-100
Rotational speed (rpm)	5-100	200-1000

3.2 The Effects of Different Dimple's Bottom Profiles on The Load-Carrying Capacity

The effect of spherical and conical dimple bottom profiles on load-carrying capacity at various eccentricity ratios is presented in Figure 7 and Figure 8.

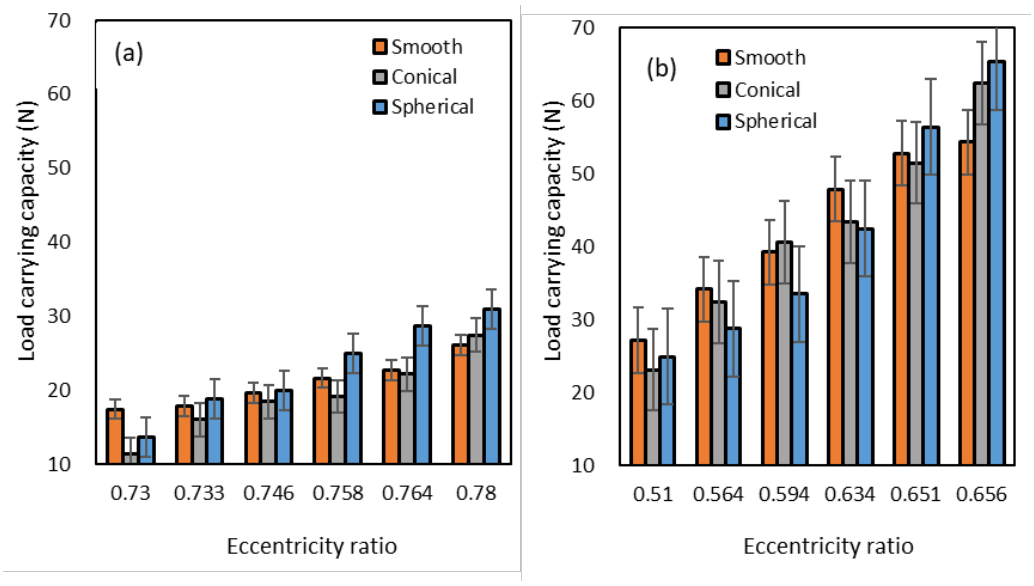

Figure 7: The load carrying capacity at a shaft speed of 200rpm (left) and 1000rpm (right)

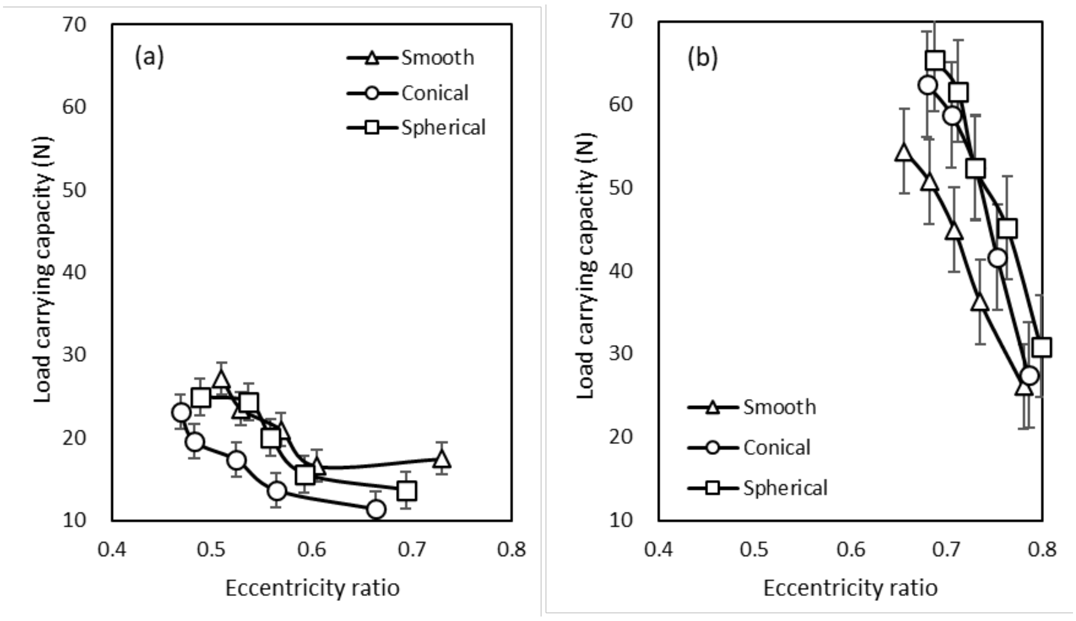

Figure 8: The load-carrying capacity at a radial load of 10N (left) and 100N (right)

The previous study suggested that surface texturing might have both positive and negative impacts on journal bearing performance [18,29], depending on various factors such as dimple geometry, density, lubricant properties, and the operational conditions of the bearing. Generally, it was observed that load-carrying capacity increased with an increasing eccentricity ratio at a fixed load, while it decreased with an increasing eccentricity ratio at a fixed speed. More simply, load-carrying capacity increased with increasing radial load and shaft speed.

At a speed of 200 rpm, the spherical dimple shape exhibited 20.11% and 12.58% higher load-carrying capacity than the conical shape at low and high eccentricity ratios, respectively. Meanwhile, at a speed of 1000 rpm, the spherical shape recorded only 7.66% and 4.75% higher load-carrying capacity than the conical shape at low and high eccentricity ratios, suggesting that the advantage of the spherical shape is more pronounced at lower shaft speeds.

Additionally, at a radial load of 10N, both dimpled surfaces exhibited lower load-carrying capacity than the smooth surface, indicating that at a fixed low load, surface texturing negatively impacted load-carrying capacity. This phenomenon might be attributed to the weak squeeze effect experienced by the textured surface. At a low load of 10N, there was no significant pressure drop in the inlet zone of the dimpled areas, leading to weaker lubricant inflow into the contact region [31, 32]. Conversely, at higher radial loads, a greater pressure drop at the leading edge of the dimple resulted in increased lubricant flow into contact, thereby improving load-carrying capacity, as observed at a load of 100N.

Regarding dimple geometry, the conical shape featured sharper edges and a wider divergence wedge at the inlet zone compared to the spherical shape, which had a gentler gradient. According to Nanbu et al. [28], sharp edges and divergence wedges contribute to pressure drops, with sharper edges causing deeper pressure drops. Consequently, the conical shape, with its sharper edges, was expected to experience a higher pressure drop, leading to a stronger squeeze effect and increased lubricant flow to the contact surface, thereby improving load-carrying capacity. However, the spherical shape's larger volume overshadowed the high-pressure drop effect of the conical shape's sharper edges. As a result, the spherical shape exhibited 12.58% and 4.75% higher load-carrying capacity than the conical shape at low and high eccentricity ratios, respectively.

3.3 The Effects of Different Dimple's Bottom Profiles on The Minimum Oil Film Thickness

The graph of minimum oil film thickness for the smooth, conical, and spherical bottom shapes of dimples was plotted at various shaft speeds and radial loads using the eccentricity ratio as a reference, as presented in Figure 9 and Figure 10, respectively.

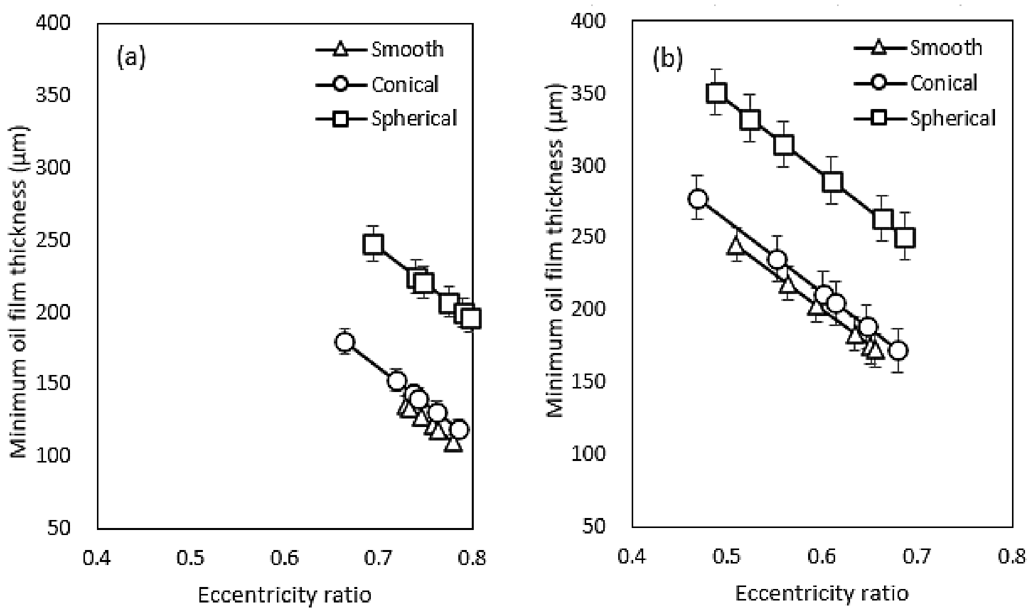

Figure 9: Minimum oil film thickness at a shaft speed of 200rpm (left) and 1000rpm (right)

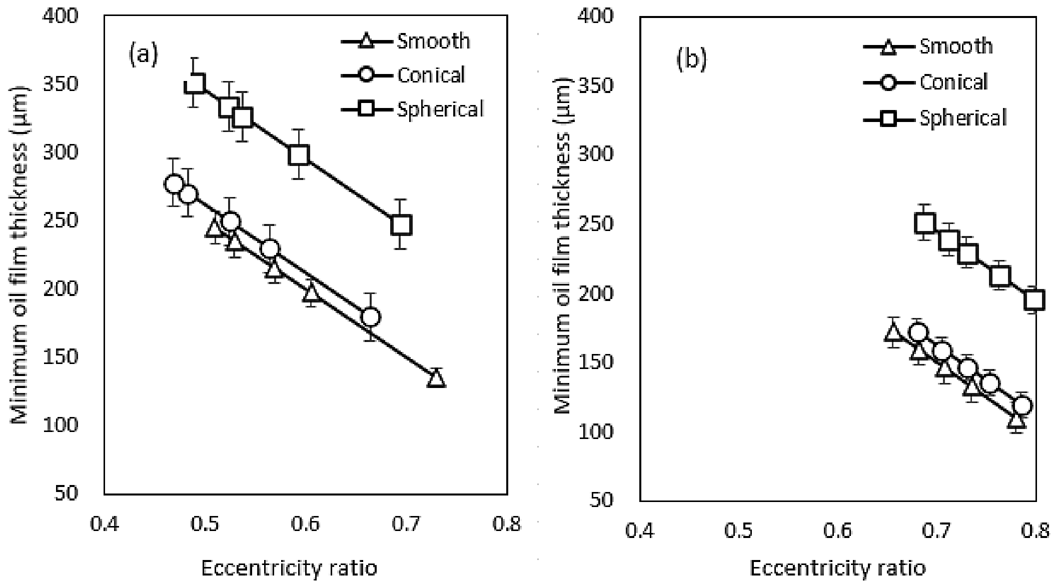

Figure 10: Minimum oil film thickness at a radial load of 10N (left) and 100N (right)

It was generally observed that the minimum oil film thickness decreased with increasing eccentricity ratio. Across all cases, the spherical shape exhibited a higher minimum oil film thickness compared to both the conical and smooth surfaces. In terms of dimple bottom profiles, the spherical shape demonstrated a 49.52% and 39.72% higher minimum oil film thickness at shaft speeds of 200 rpm and 1000 rpm, respectively. Additionally, the spherical shape showed 28.86% and 53.99% higher minimum oil film thickness compared to the conical shape at radial loads of 10N and 100N, respectively. These findings indicate that the spherical shape is more effective in enhancing minimum oil film thickness at low shaft speeds and high radial loads.

A similar observation was made by Nanbu et al. [28], who found that surface texturing on a moving surface significantly improves minimum oil film thickness compared to a smooth surface or a combination of smooth and textured surfaces. This improvement is primarily attributed to the additional lubricant flow induced by the squeeze effect, as predicted by Patir and Cheng [33]. The spherical shape, with its larger volume and stronger squeeze effect, facilitated greater lubricant inflow to the contact surface, thereby enhancing load-carrying capacity more effectively than the conical shape. Furthermore, it was suggested that the faster the textured surface moves, the more pronounced the improvement in oil film thickness.

4.0 CONCLUSION

The study analyzed the impact of different dimple bottom profiles on the shaft surface concerning journal bearing performance. The key comparisons and findings were thoroughly discussed, leading to the following conclusions:

1. The spherical shape significantly reduced the friction coefficient under all operating conditions compared to conical and smooth surfaces. This reduction was attributed to the higher dimple volume, which enhanced the squeeze effect and increased the minimum oil film thickness.
2. The spherical shape exhibited a strong squeeze effect, which improved load-carrying capacity at higher radial loads. However, at lower radial loads, the squeeze effect was weaker, resulting in minimal benefit to load-carrying capacity for both spherical and conical shapes.
3. Greater dimple depth contributed to an increase in the minimum oil film thickness. Among the tested profiles, the spherical shape provided the most significant improvement in minimum oil film thickness compared to conical and smooth surfaces.

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